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14. ABSTRACT

Atmospheric or higher pressure nonequilibrium or cold plasmas are susceptible to instabilities and the lifetime of the discharge depends various parameters such as the gas (attaching/non-attaching, atomic/molecular, pure gas/gas mixture), the applied external electric field (DC, pulsed, or AC), and the magnitude of the discharge current. Various approaches have been pursued to "stabilize" atmospheric pressure discharges by extending the lifetime of the discharge to hundreds of microseconds. The most promising stabilization approaches are based on the recognition that arc formation in high-pressure plasmas can be avoided and stable high-pressure plasmas can be generated and maintained when the plasmas are spatially constricted to dimensions of tens to hundreds of microns. These types of discharges have come to be known as microdischarges or microplasmas. This project conducted basic research in microplasmas at atmospheric or higher pressures. A further and very important objective of this project was to address the major national concern of attracting young people to science and science-related careers.

15. SUBJECT TERMS

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FINAL REPORT

Air Force Office of Scientific Research

Grant # FA9550-08-1-0332

"BASIC RESEARCH IN MICROPLASMAS"

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I. SUMMARY OF ACCOMPLISHMENTS

Under the support of AFOSR Grant # FA9550-08-1-0332, our research laboratory at the Saint Peter's College has pursued basic research into the science of microplasmas. The motivation for this work was due to the programmatic interest of the Plasma and Electro-Energetic Physics Program at AFOSR which is interested in the science of atmospheric or higher pressure non-equilibrium (cold) air plasmas. These cold air plasmas are susceptible to instabilities. The lifetime of these depends on the gas (attaching/non-attaching, atomic/molecular, pure gas/gas mixture), the applied external electric field (DC, pulsed, or AC), and the magnitude of the discharge current. Various approaches have been pursued to "stabilize" atmospheric pressure air discharges by extending the lifetime of the discharge to hundreds of microseconds. One such stabilization method of atmospheric cold plasmas has been achieved through the introduction of dielectric or insulating material on one or both electrode surfaces that leads to a distribution of discharges on the electrode surfaces and under certain conditions leads to a diffuse discharge at about atmospheric pressure with gap widths up to several centimeters. Some of the more recent and most promising stabilization approaches are based on the recognition that arc formation in high-pressure plasmas can be avoided and stable high-pressure plasmas can be generated and maintained when the plasmas are spatially constricted to dimensions of tens to hundreds of microns. These types of discharges have come to be known as microdischarges or microplasmas, the research subject matter of this funded project. This three year project conducted basic research in microplasmas at atmospheric or higher pressures focusing on microhollow cathodes, micro jets, and similar microplasma sources. It is notable to mention that this research work was further enhanced by a second AFOSR Grant # FA9550-09-1-0284, which established the *Center for Microplasma Science and Technology* (CMST). The final report for this second funded project further supplements and connects with the described work this current final report. A further and very important objective of this project was to seek to address the major national concern of attracting young people to science and science-related careers. Members of groups that are traditionally underrepresented in science, mathematics, engineering, and technology were especially attracted to help in addressing the acute low number of minority college students majoring in physics. A six month no cost extension was requested for this research project to allow graduate student Ms. Ruixue Wang of Polytechnic Institute of NYU and Peking University to finish here work on the MicroJet project in our laboratory. This project utilized the basic research in microplasmas as a vehicle to attract and encourage American-citizen students as early as high school to consider pursuing scientific careers in plasma science and other allied scientific disciplines. This project had a close collaborative relationship with Saint Peter's Preparatory School in Jersey City, New Jersey from where the high school student researchers where attracted for summer research opportunities.

II. DESCRIPTION OF MAJOR ACCOMPLISHMENTS

2.1 Study of Microhollow Cathode Discharge based Plasma MicroJet

The Plasma MicroJet (PMJ) is based on Microhollow Cathode Discharge (MHCD) concept. Typical MHCD setup comprises a cathode with micro-hollow structure and an anode (with a similar micro-hollow structure, which is aligned with that in the cathode) separated by a dielectric layer of dimensions below 1 mm. When working gas (e.g. air, helium or helium/oxygen mixture, etc.) is pushed through the opening of this structure and DC power is supplied, a spatially well-defined atmospheric-pressure PMJ can be sustained in ambient air.

A schematic diagram of the device is shown in Figure 1. Two metal electrodes are separated from each other by a dielectric layer of ~ 0.5 mm thickness. The openings in the two electrodes are ~0.8 mm in diameter. The high-voltage electrode is completely embedded in the device and powered by a DC power supply (Glassman). The outer electrode is grounded for safety considerations. Although both positive and negative high voltages are able to generate and sustain the PMJ, we used negative high voltage in most studies. A ballast resistor of 5 kΩ followed by a current monitoring resistor of 100 Ω is inserted between the powered electrode and the DC power supply.

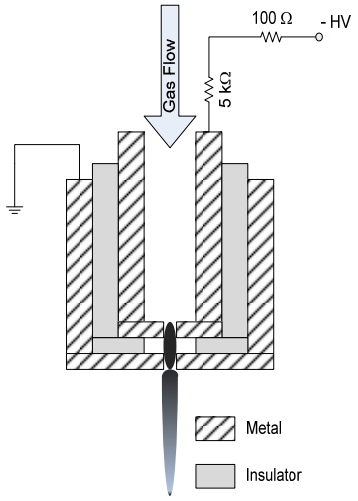


Figure 1. A schematic diagram of the Plasma MicroJet device

(1) Air as the working gas

Compressed air at a gas flow rate of approximately 2-4 slm was used as working gas. The discharge sustaining voltage is in the range of 400 – 600 V with an operating current in the 3 – 35 mA. Under these operating conditions, a PMJ of ~1 cm visible length is generated. The visual appearance of the PMJ depends on the air flow rate, opening size and the electric current provided by the power supply. An exemplary picture of the device working in air is shown in Figure 2. The power efficiency of the device (defined as power deposited into the discharge relative to the total power drawn from the power

supply) is approximately 80%. The temperature of the grounded electrode reaches approximately 70 °C at a current of 20 mA and a flow rate of 2 slm. The gas temperature 1 cm away from the nozzle was measured to be around 38 °C.

Figure 2. An illustrative picture of PMJ operating in air with compressed air as working gas

To identify the reactive species that are generated in the discharge and subsequently expelled, emission spectra was recorded in the range from 200-900 nm along the axial direction of the PMJ with a 0.75 m spectrometer (Princeton Instrument/Acton Spectra Pro 2750) and an intensified Charged Coupled Device (ICCD, Princeton Instrument I-Max-1024). Light was directly sampled via a quartz fiber optics without going through any lenses.

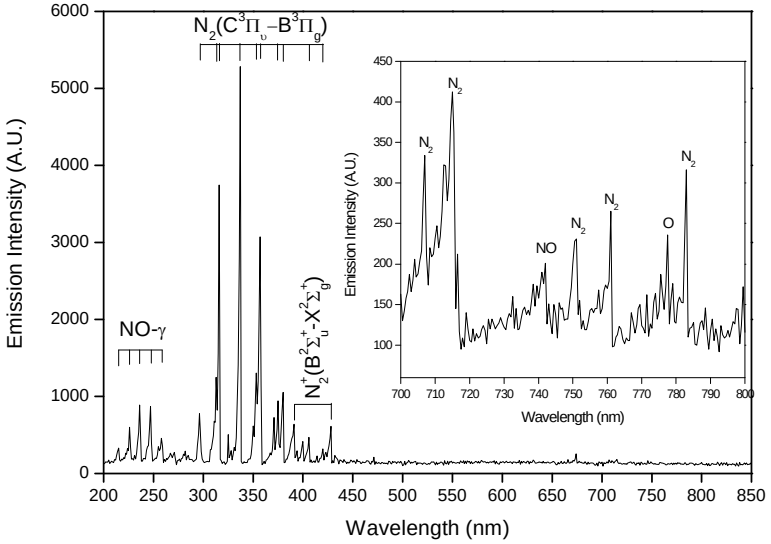
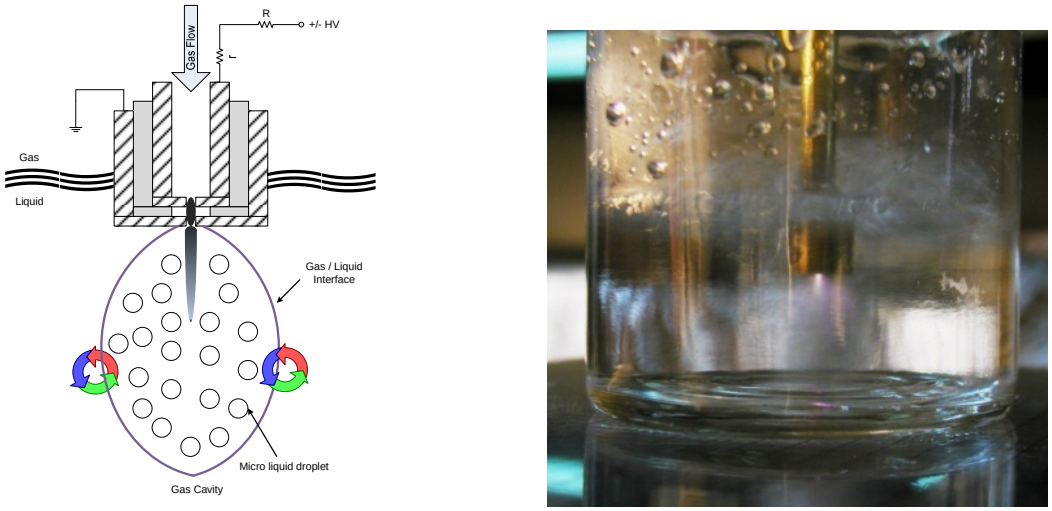


Figure 3. A typical optical emission spectrum of the PMJ device working in air; Inset shows the emissions in the near infrared region.

Figure 3 shows a typical optical emission spectrum of the device working in air. The whole spectrum was dominated by N_2 lines due the excessive nitrogen in air. Near infrared spectrum (inset) shows emissions from reactive species such as NO (742.0 nm) and O (777.2 nm). Some emission from NO was also observed in the ultraviolet region from 215 nm to 315 nm.

When the exit nozzle of the PMJ device was immersed in water (here de-ionized water or sterile water was used), a quasi-steady gas cavity inside the water sustained the PMJ. A schematic diagram as well as a photo of the PMJ sustained in water is shown in Figure 4. No gas cavity is clearly visible due to the long exposure time of the picture.



(a) (b)

Figure 4. PMJ working in water: (a) a schematic diagram and (b) a picture of the PMJ sustained in a quasi-steady gas cavity in water.

The pH values of the three liquid media were evaluated with a Microprocessor pH-meter (HANNA pH213 Instruments, USA). An increase of the acidity of the liquid was always observed. Figure 5 shows the pH changes 7.5 to about 3.0 in about 8 minutes. This is believed to be due to NOx from the air plasma reacting with water. The concentrations of nitrate anions (NO_3^-) and nitrite anions (NO_2^-) in sterile water were measured with a high-performance liquid chromatography, HPLC (Dionex ICS-2500 equipped with an ED50 electrochemical detector and a DIONEX ASRS 4-mm suppressor module). 25 μL samples were injected into the system for analysis. The results of NO_3^- and NO_2^- are shown in Figure 6. This is attributed to the multistep reaction of plasma-generated reactive species, including NO_x, O, O_3, with water at gas-water interface (the quasi-steady gas cavity surface as well as on the surfaces of micro droplets of liquid inside the gas cavity). The concentrations of nitrite anions (NO_2^-) and nitrate anions (NO_3^-) in sterile water were monitored with HPLC and the result is shown in Figure 5 (experiments were repeated 3 times). The concentrations of NO_2^- and NO_3^- increase steadily from 0 mg/L and 0.7 mg/L to about 37 mg/L and 21 mg/L, respectively, over 20 minutes of PMJ treatment. It is important to note that these experiments were usually conducted after all other experiments were completed (typically in the span of 2-3 hours). A potential source of systematic error might be due to the fact that NO_2^- tends to be oxidized to NO_3^- in a liquid over time.

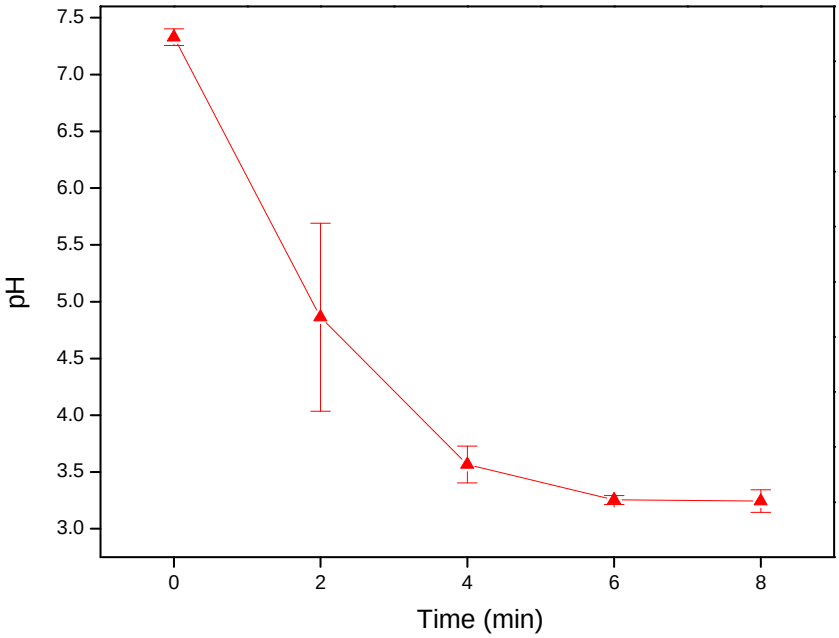


Figure 5. pH change of water versus time when plasma was directly immersed in water

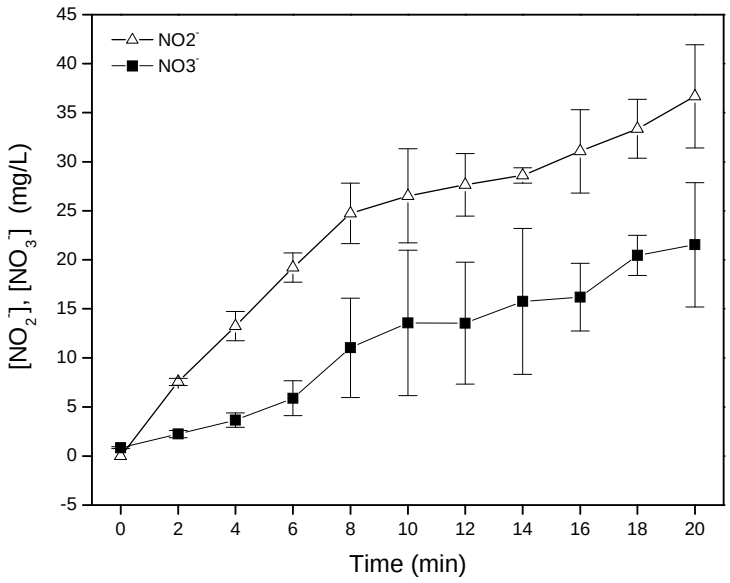


Figure 6. The concentration of NO_2^- and NO_3^- in sterile water after PMJ treatment

(2) Helium/Oxygen, Argon/Oxygen and Argon/Nitrogen/Oxygen as working gas

Helium/Oxygen as working gas

When pure Helium (99.996%) mixed with O_2 (at different volume concentrations) was used as working gas, the PMJ appears quite differently from the air situation. Images of the PMJ taken with a Nikon D300S (equipped with a Nikon macro lens) were used to evaluate the length of the visible plume as a function of discharge current (ranging from 2 mA to 40 mA) and oxygen concentration (ranging from 0% to 4%). Figure 7 shows a few exemplary images of the PMJ with He/O2 as working gas and figure 8 summarizes the jet length at different discharge current and oxygen concentrations at a flow rate of 2 slm. The general trend is when O_2% ≤1%, jet length increases with the increase of current, while when O_2% >1%, this phenomenon is not as obvious.

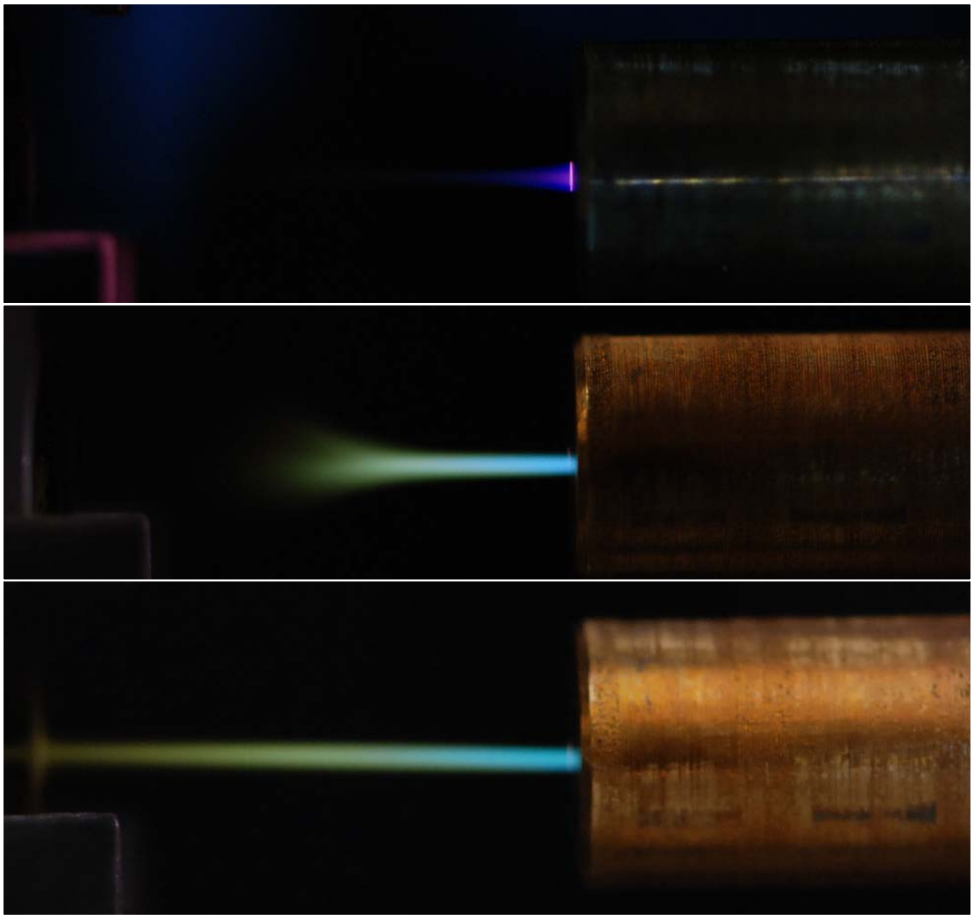


Figure 7. A few exemplary images of PMJ with He/O_2 (2%) as working gas.

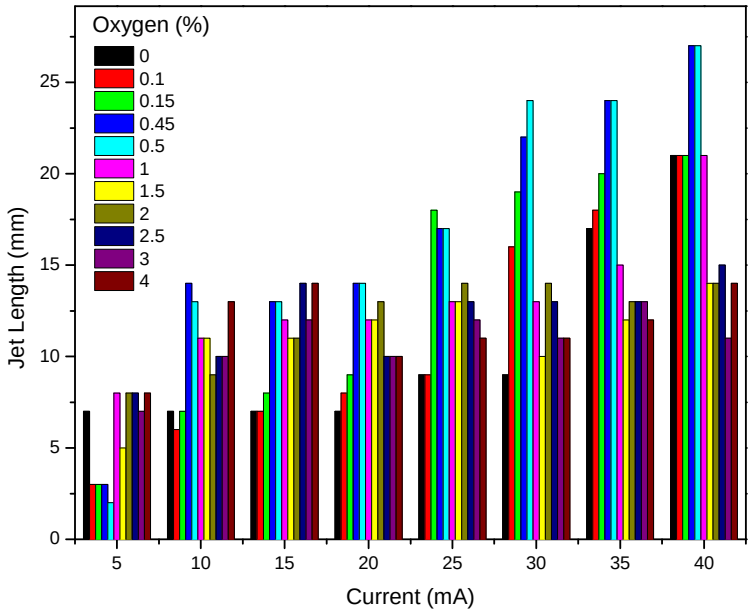


Figure 8. Summary of the visible length of the He/O_2 (2%) PMJ with different discharge current and oxygen volume concentration (gas flow rate: 2 slm)

At a flow rate of 2 slm, current-voltage characteristics of the plasma jet was studied with different oxygen concentration (0-4%). Two distinctive regions were observed, as shown in Figure 9. In region 1, the sustaining voltage decreases with the increasing current – this negative differential resistance (NDR) is quite common for hollow cathode discharge. This hollow cathode effect was a result of electrons accelerating across the cathode fall and oscillating in the region around the cylindrical cathode, efficiently transferring their energy to the gas and resulting in a discharge whose current increased when the voltage decreased. In region 2, the sustaining voltage stays constant when the current is increased. This region corresponds to a normal glow discharge, where the plasma expanded into the cathode tube. The turning point of NDR mode to normal glow discharge shifted to higher current with the increase of the O_2 concentration. The overall sustaining voltages also increased with the increased O_2 concentration. The flow rate (1 to 4 slm) doesn't affect I-V characteristics much. All data have been measured for 3 times to minimize the error. It has to be noted that current was monitored by measuring the voltage drop on the current monitoring resistor. The voltages were obtained by subtracting the voltage output from the power supply by the voltage drop on the ballast resistor.

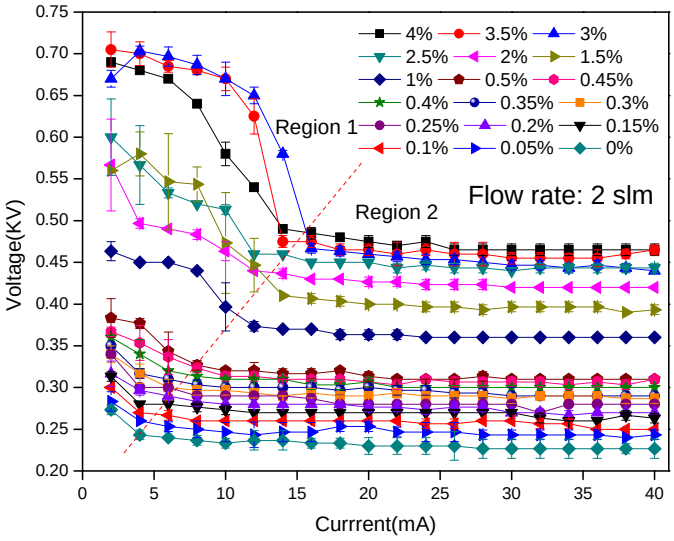


Figure 9. Current-Voltage characteristics of He/O_2 PMJ with different oxygen concentration at a gas flow rate of 2 slm

Optical emission spectra were taken along the axial direction to evaluate the species created in the PMJ. A typical emission spectra is shown in figure 10. Major peaks are from helium emissions, while strong atomic oxygen emissions at 777 and 844 nm were also observed. Water from the surrounding air was disassociated and excited, with both OH (A-X) band (306–309 nm) and H_α (656 nm) observed (insets in figure 10), although very weak. Copper emissions were also observed in the UV region due to the choice of the electrode material.

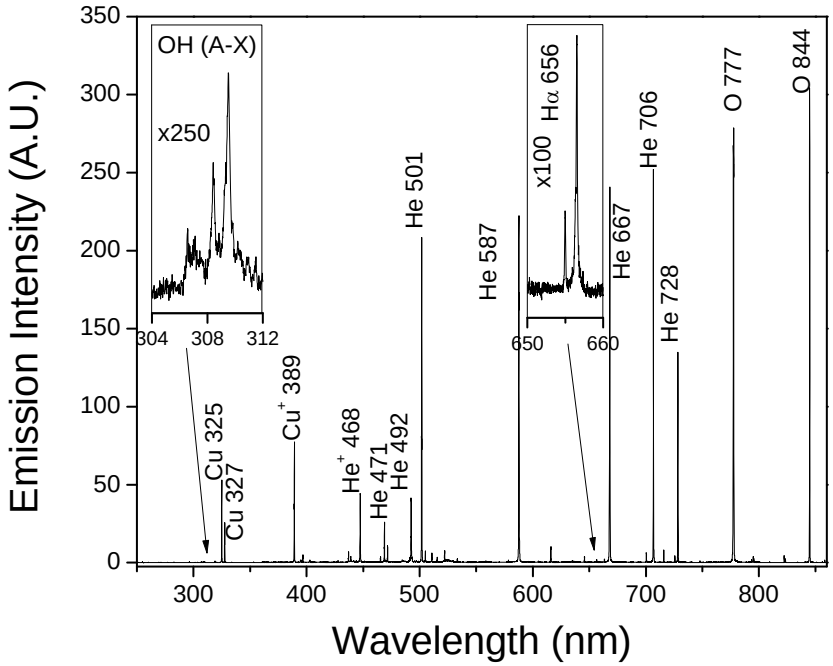


Figure 10. End-on optical emission spectrum of He/O_2 PMJ in air

The O (777nm) and He (706nm) emission intensities at various oxygen percentage (0 to 4%), gas flow rates (1 to 6slm), discharge power (3 to 15W) from end on. Emission spectra was also recorded from side-on along the jet at various distances.

Figure 11 shows the effect of the O_2 percentage on the relative intensity of the atomic oxygen line (777nm), along with the He (706nm) measured from end-on and side-on at a distance of 3 mm from the nozzle.

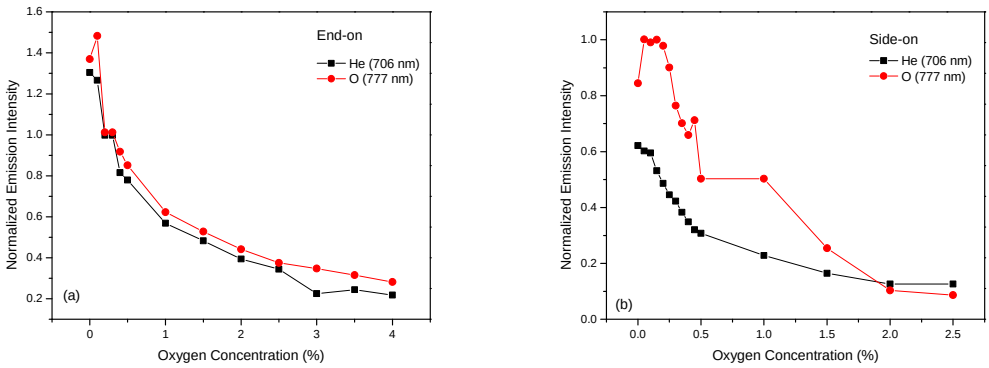


Figure 11. Normalized emission intensities of O (777nm) and He (706nm) at varying oxygen percentage recorded from (a) end-on and (b) side-on at a distance of 3 mm away from the exit nozzle

He (706nm) and O (777nm) emission intensity was recorded at different flow rates. The advantage of decreasing flow rate is that it is cost-saving, and it would be practical for use in small openings and for vulnerable tissues. However, due to the lower flow, more air will diffuse into the discharge and this will change its characteristics and the gas temperature will increase due to the low convection. In this series of experiments, the He/O_2 volumetric ratio is kept constant at an optimal value of 0.3.vol-%, the discharge power is kept at 11 W. Figure 12 shows the normalized intensity of selected emission lines as a function of the flow rate. It can be clearly seen that an increase of the total flow rate leads to an increase of the emission intensity of the O (777nm) line in the side-on spectra. Interestingly, it is quite opposite in the end-on spectra, that is, the emission intensity of the O (777nm) decreases with the increase of total flow rate. This phenomenon is directly attributable to a more significant convective transport along the jet axis and the oxygen atom (777nm) seems to expand to side than transport along the axis. The emission line of He(706nm) don't change too much for both systems. This can be explained by the fact that the upper energy level of the O (777nm) is lower than the upper energy level of He(706nm)(10.74eV and 22.72eV, respectively).

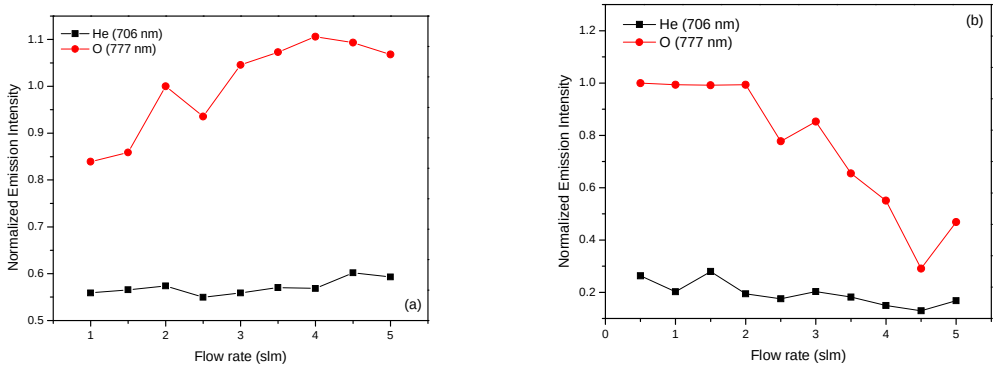


Figure 12. Normalized emission intensity of He (706nm) and O (777nm) as a function of flow rate recorded from (a) side-on and (b) end-on.

As we kept the gas flow rate at 2 slm and oxygen concentration at 0.3% and change the input power from 3 to 15W, the intensities of He(706nm) and O(777nm) increased both in side-on end-on emission spectra, as shown in figure 13. It is believed that even though a small percentage of O_2 was added to helium, electrons dissipated more than 90% of the absorbed power through collisions with oxygen molecules and the dissipated power through collisions with helium is less than 10%. This explains our experiment results, most of the power were used to excite oxygen molecules and less left for the exciting of helium, so the intensity of O (777nm) changed a lot compared to that of He (706nm).

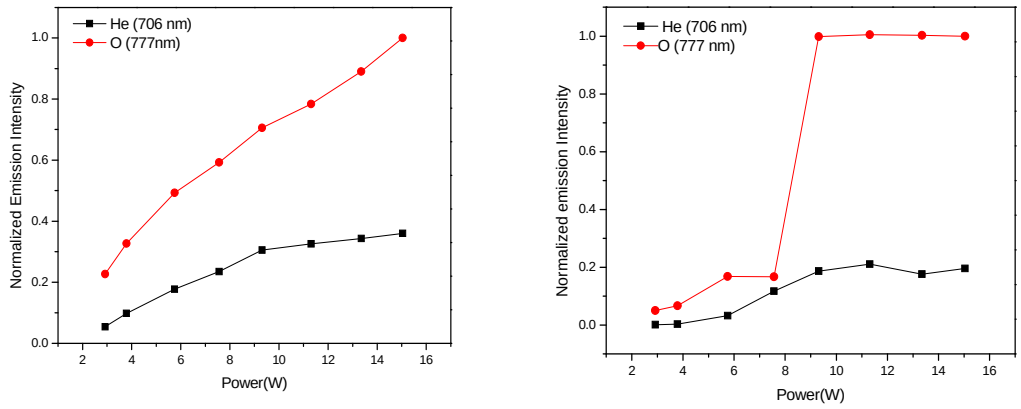


Figure 13. The density of He(706nm) and O(777nm) as a function of input power for (a) side-on spectroscopy and (b) end-on spectroscopy

In the exemplary images of the PMJ with He/O_2 as working gas, color gradient along the PMJ can be observed. He (706nm) and O (777nm) emissions were monitored along the PMJ up to 8 mm. Figure 14 shows their intensities at various distances and input powers. Both showed the same general trend that the emission intensity increase with the input power while decreased with the distance which meant that the production of excited metastable He and atomic O mainly come from the upstream of the plasma jet.

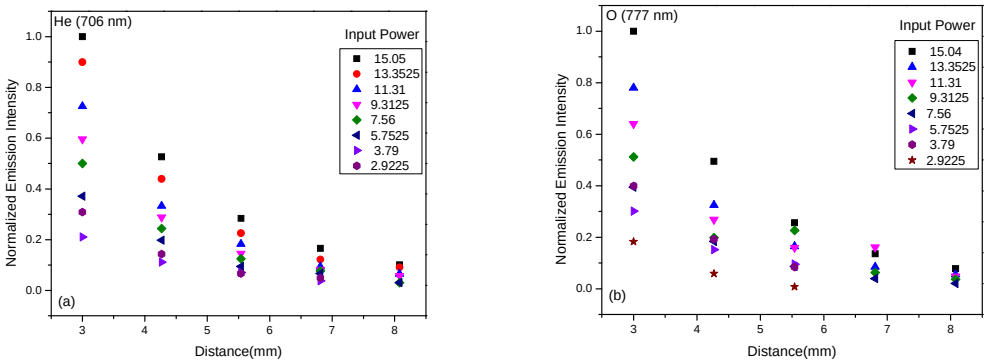


Figure 14. Side-on emission intensity with different input power at various distances from jet exit for (a) He(706nm) and (b) O(777nm). The total flow rate was kept in 2slm while oxygen percentage was kept in optimal percentage (0.3%).

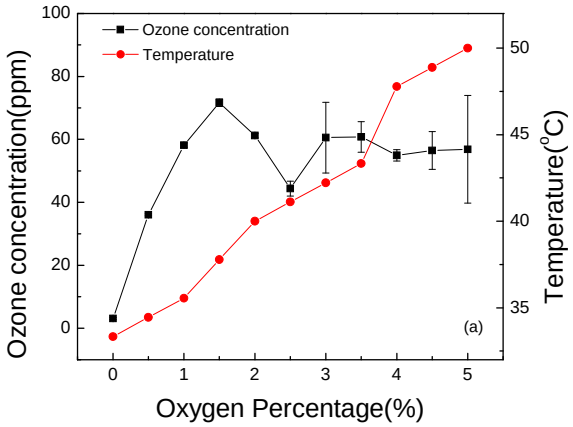
For both end-on and side-on spectra, when pure helium was used as working gas, strong O atom was also detected in the system which means air surrounding the PMJ reacts with the excited species. The production of O might be limited by the availability of electrons and other excited species such as He metastable atoms in the (2^1S) and (2^3S) states. He metastable will be mentioned as He* from now on. The rapid spatial decay of the excited neutral He atomic line (706nm) indicates that a significant fraction of He* atoms quenched by Penning ionization with O_2 molecules (reaction 1) and a majority of plasma electrons are used to ionize(reaction 2), dissociate(reaction 3, and 4)and excite the O_2 molecules(reaction 5) instead of the He excitation. What's more , it seems that the very few of He* atoms were used for the Penning ionization of the N_2 molecule(reaction 6), because no N_2^+ ion (391nm) were detected in side-on system and only weak peak were found in end-on system when pure He was input.

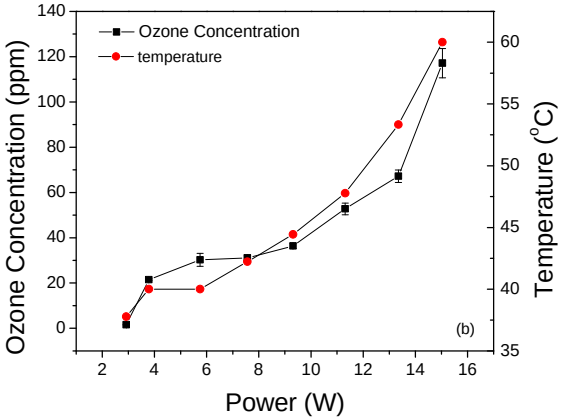
$$He^* + O_2 \rightarrow He + O_2^+ + e \quad (1)$$
$$O_2 + e \rightarrow 2e + O_2^+ \quad (2)$$
$$O_2 + e \rightarrow e + [O(^1D) \text{ or } O(^1S)] + O \quad (3)$$
$$O_2 + e \rightarrow 2O + e \quad (4)$$
$$O_2 + e \rightarrow O_2(b^1\Sigma^+_g) + e \quad (5)$$
$$He^* + N_2 \rightarrow He + N_2^+ + e \quad (6)$$

In the experiments, ozone concentration was also monitored with an ozone analyzer ((Eco sensors, INC, Model UV-100). We found that ozone concentration is closely

dependent on the operating parameters. In the beginning, the ozone concentration increased rapidly with the increased oxygen concentration, reached as high as 72 ppm when the oxygen percentage was 1.5% and then stayed constant in a higher oxygen percentage (Figure 14(a)). The ozone concentration increased rapidly with the increased input power and flow rate (Figure 14 (b) and c)). It should be noted that, He/O_2 (2%) can produce 0.005 to 120 ppm of ozone. However, ozone analyzer measures ozone concentration at the downstream of the PMJ.

A thermal couple was used to monitor the temperature of the PMJ at a fixed distance of 2 cm with the same varying parameters. The temperature data is also shown in figure 14. With the increase of oxygen percentage, the gas temperature increases more or less linearly. The plasma jet is at 34℃ when pure helium was used as working gas and eventually the temperature reaches 50 ℃ with 5% O_2 added into the stream. The temperature shows the same dependency on input power. Flow rate, however, affects the temperature the most. For low flow rate, the temperature increases with increasing flow rate until it reaches a maximum value of 52℃ at 1.5 slm. Further increasing the flow rate decreases the gas temperature and it approaches a value of 43℃ at 5 slm.





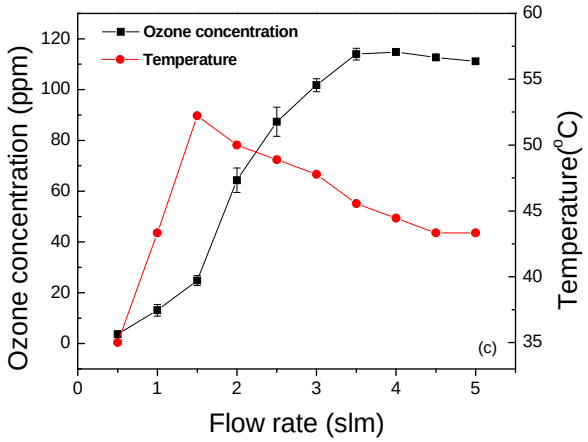


Figure 14. Ozone concentration and temperature of plasma jet at different (a) Oxygen concentration, (b) power (c) flow rate.

He/O_2 PMJ was also submerged in distilled water. Electron Spin Resonance (ESR) Spectroscopy was used to detect the radicals (such as hydroxyl radical, singlet oxygen and super oxide anion) produced in water. These species are extremely short lived (life time is from ns to μs). Detecting these species involves spin-trap technique where a spin trap reagent is used to capture the short-lived radicals and form adducts that have much longer life time. In all experiments, a volume of 1 mL liquid was used. Plasma treatment was limited to 20 seconds to optimize the outcome signals. Each final product was imbibed by a capillary and detected in the resonator cavity of an ESR spectrometer (ER-200D-SRC, Bruker Ltd) operated at room temperature. The parameters of the ESR spectrometer were set as the following: central field: 342.00 mT; sweep width: 20 mT; microwave frequency: 9.53 GHz; modulation frequency: 100 kHz and microwave power: 20 mW. Figure 15 (a) and (b) show ESR spectra of DMPO-OH (spin adduct of hydroxyl) and TEMPO (spin adduct of singlet molecular oxygen), respectively.

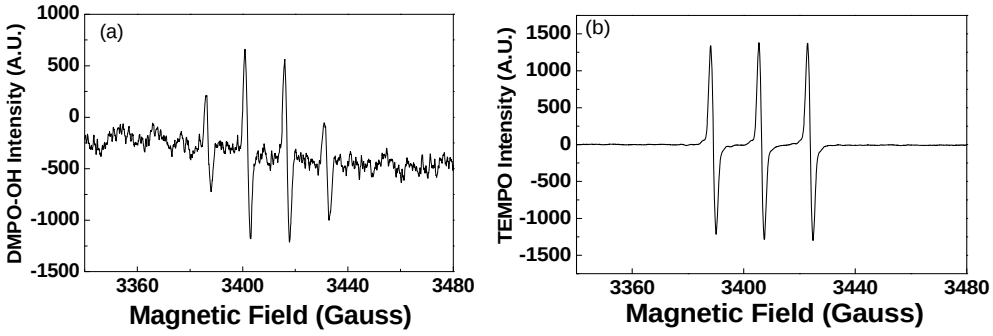


Figure 15. (a) and (b) show ESR spectra of DMPO-OH (spin adduct of hydroxyl) and TEMPO (spin adduct of singlet molecular oxygen), respectively.

DMPO can also spin trap $^{\cdot}O_2^-$, or rather $HOO^{\cdot}$ (the conjugate acid of $^{\cdot}O_2^-$), forming spin adduct DMPO-OOH, which typically shows 12 consecutive peaks in ESR spectrum. However, the reaction rate constant between DMPO and $\cdot O_2^-$ is much lower ($<10^2$ $M^{-1}\cdot sec^{-1}$ at pH 7) than that between DMPO and $^{\cdot}OH$ (10^9 $M^{-1}\cdot sec^{-1}$). On the other hand, DMPO-OOH tends to quickly decompose into DMPO-OH, making the direct detection of $\cdot O_2^-$ through spin trapping with DMPO rather difficult. Therefore, we consider the following pathway between $^{\cdot}O_2^-$ and $^{\cdot}OH$, and use the change of DMPO-OH signal to infer the existence of $\cdot O_2^-$: In water, $\cdot O_2^-$ can react with protons to form H_2O_2 (self-dismutation). The produced H_2O_2 can further covert to $^{\cdot}OH$, which is enormously accelerated by the catalysis of transition metals such as Fe^{2+} (Fenton reaction) and Cu^+. Cu^{2+} can be reduced to Cu^+ by $^{\cdot}O_2^-$ through oxidation and reduction. Since copper is used as the electrodes, both Cu^{2+} and Cu^+ were detected in this system via HPLC. These reactions are summarized in equations (1)-(3) below. The sum of reactions (2) and (3) yields so called Haber-Weiss reaction, and is listed as equation (4).

$$2\,^{\cdot}O_2^- + 2H^+ \rightarrow H_2O_2 + O_2 \quad \text{(self dismutation)} \tag{1}$$

$$H_2O_2 + Cu^+ \rightarrow {}^{\cdot}OH + OH^- + Cu^{2+} \quad \text{(Fenton reaction)} \tag{2}$$

$$Cu^{2+} + {}^{\cdot}O_2^- \rightarrow Cu^+ + O_2 \quad \text{(Oxidation and reduction)} \tag{3}$$

$${}^{\cdot}O_2^- + H_2O_2 \rightarrow {}^{\cdot}OH + OH^- + O_2 \quad \text{(Haber-Weiss reaction)} \tag{4}$$

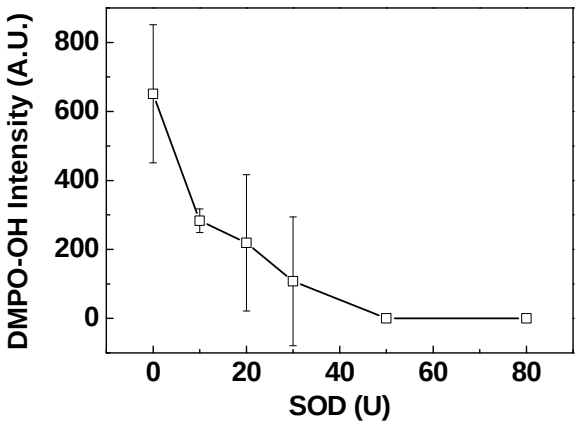


Figure 16. The effect of SOD on DMPO-OH signal. (Half height of the 2nd peak of the quartet spectrum was chosen to represent DMPO-OH intensity)

Various amounts of SOD were added into the system prior to plasma treatment. The intensity of DMPO-OH signal (half height of the 2nd peak again taken as the reference) decreases with the increase of SOD and reaches zero when SOD in the liquid is around 50 U (Figure 16). This means that $^{\cdot}O_2^-$, although produced in the system, likely converts completely into $^{\cdot}OH$ via Haber-Weiss reaction (catalyzed by Cu^+).

Future work:

Future work on PMJ will be focused on the following aspects:

1. Self-pulsed mode was well studied in the static situation. However, no study has ever been done in the gas flow situation. Reactive species produced in the self-pulsed mode can be quite different from the DC mode. Therefore, study of self-pulsed mode, including synchronize an ICCD camera to take fast images will be one of the future focuses.

2. Single and double jet interaction with inorganic and organic surfaces, in particular the study of the outgas at the surface with the assistance of a GC/MS or PTR-MS.

3. Low kilohertz high voltages (duration in 100s of ns) can reduce temperature considerably. These power supplies were used extensively in dielectric barrier discharges. One of the future research topics will be PMJ operated with pulsed DC power.

III. PUBLICATIONS

Conference Presentations and Posters:

5th International Workshop on Microplasmas: Fundamentals and Applications, March 1-5, 2009, San Diego, CA, USA

1. W. Zhu, J. Lopez and K. Becker, Atmospheric Pressure Plasma Micro Jet - Its Interaction with Bacteria in Air and in Liquid Media (Invited Talk)
2. W. Zhu, L. To, J. Lopez and K. Becker, Direct Current Cathode Boundary Layer Xenon Discharges (Poster)
3. J. Lopez, D. Jacome, W. Zhu, M. Figus and K. Becker, Study of the Operational Properties of the Capillary Plasma Electrode (CPE) Discharge (Poster)
4. J. Lopez, W. Zhu and K. Becker, Time-Resolved Investigations of a Fast-Pulsed Dielectric Barrier Discharge (Poster)

2nd International Conference on Plasma Medicine, March 16-20, 2009, San Antonio, Taxas, USA

1. W. Zhu, J. Lopez and K. Becker, Interaction of an Atmospheric-Pressure DC Plasma Micro Jet (PMJ) with Bacteria and Liquid Media (Talk)

37th IEEE International Conference on Plasma Science, June 20-24, 2010, Norfolk, VA, USA

1. W. Zhu, J. Lopez and K. Becker, Optical emission study of a direct-current, atmospheric-pressure non-thermal Plasma Micro Jet (Talk)
2. J. Mahoney, W. Zhu, J. Lopez, V. Johnson, Electrical and Optical Emission Measurements of a Capillary Dielectric Barrier Discharge (Poster)
3. V. Johnson, W. Zhu, L. To, J. Lopez, Self Organization Trends in Cathode Boundary Layer Discharge (CBLD) Devices for Various Cathode Materials (Poster)

63rd Gaseous Electronic Conference, October 4-8, 2010, Paris, France

1. W. Zhu, J. Lopez and K. Becker, Optical Emission Study of a direct-current, atmospheric-pressure non-thermal Plasma micro jet (Poster)

6th International Workshop on Microplasmas, to be held on April 3-6, 2011, Paris, France

1. W. Zhu, V. S. Johnson, R. Wang, J. Lo Re, J. Mahoney and J. L. Lopez, Atmospheric Pressure Plasma Jet Matrix (Talk)
2. J. M. Mahoney, W. Zhu, V. S. Johnson, and J. L. Lopez, Electrical and Optical Emission Measurements of a Capillary Dielectric Barrier Discharge in Atmospheric Pressure Air and Argon (Poster)
3. V. S. Johnson, W. Zhu, J. Lopez, Cathode Boundary Layer Discharges with Various Cathode Materials (Poster)
4. R. Wang., J. Lo Re, W. Zhu, K. H Becker and J. L. Lopez, Characterization of a DC-Driven, Atmospheric-pressure, Non-thermal He/O2 Plasma Microjet (Poster)
5. J. M. Mahoney, W. Zhu, D. Palacios, and J. L. Lopez, Vacuum Ultraviolet (VUV) Emission from a Fast-pulsed Dielectric Barrier Discharge in Argon (Poster)
6. V. S. Johnson, W. Zhu, S. Sivaram, R. Wang, J. Lo Re, J. M. Mahoney, J. L. Lopez, Low Temperature Atmospheric Pressure Helium Plasma Jet in Flexible Tubings (Poster)

Peer Reviewed Journal Publications:

- W. Zhu and J.L. Lopez. DC Nonthermal Atmospheric-pressure Plasma Microjet. Plasma Sources Science and Technology. In Press (2012).
- D.A. O'Brien, W. Zhu, and J.L. Lopez. Student Experiences with Plasma Phenomena. IEEE Transactions on Plasma Science. Vol. 39, Issue 11, p. 2584-2585 (2011).
- R. Wang W. Zhu, J.J. Lo Re, J. Zhang, J. Fang, and J.L. Lopez. Laminar-to-Turbulent Transition of a DC Helium/Oxygen (2%) Plasma Microjet. IEEE Transactions on Plasma Science. Vol. 39, Issue 11, p. 2374-2375 (2011).
- V.S. Johnson, W. Zhu, R. Wang, J.J. Lo Re, S. Sivaram, J. Mahoney, and J.L. Lopez. A Cold Atmospheric-Pressure Helium Plasma Generated in Flexible Tubing. IEEE Transactions on Plasma Science. Vol. 39, Issue 11, p. 2360-2361 (2011).
- J. Mahoney, W. Zhu, D. Palacios, V.S. Johnson, and J.L. Lopez. Footprints of a Fast- Pulsed Dielectric Barrier Discharge. IEEE Transactions on Plasma Science. Vol. 39, Issue 11, p. 2182-2183 (2011).
- J. Mahoney, W. Zhu, J. Lopez, V. Johnson, Electrical and Optical Emission Measurements of a Capillary Dielectric Barrier Discharge, the European Physical Journal D: Atomic, Molecular, Optical and Plasma Physics, 60, (2010) 441
- P. Sun, Y. Sun, H. Wu, W. Zhu, J. Lopez, W. Liu, J. Zhang, R. Li and J. Fang, Atmospheric pressure cold plasma as an antifungal therapy, Applied Physics Letters, 98 (2011) 021501

- K. H. Becker, H. Kersten, J. Hopwood, and J. L. Lopez. Microplasmas: scientific challenges & technological opportunities. European Physics Journal D. Vol 60, 437- 439 (2010)
- J. Lopez. *Ozone Generation with Cold Plasmas for Water Treatment Processes*. Chapter 2 in Biological and Environmental Applications of Gas Discharge Plasmas. Editor - Graciela Brelles-Mariño. Nova Science Publisher Inc. p. 33-48 (2010)
- G. Vezzú, J.L. Lopez, A. Freilich, and K. Becker. *Optimization of Large-Scale Ozone Generators.* IEEE Transactions on Plasma Science. Vol. 37, No. 6, p. 890-896 (2009).

IV. PATENTS

There were no patents filed as a result of this research project work.

V. STUDENTS AND PERSONNEL SUPPORTED

Students:

There was a total of 1 graduate student, 9 undergraduate students, and 12 high school students from Saint Peter's Preparatory School directly supported by this project. There was also collaborations with various local area public high schools and the American Chemical Society's SEED program that supported student researchers and we hosted in our research laboratory. A few research contributions of the various student participants are highlighted:

- Kamal Shah, high school students, McNair Academic High School, Project: Microhollow Cathode Discharge Plasma Microjet, electrical and optical characterizations. (2009-2010)
- Yacine Fares, high school students, McNair Academic High School Project: Imaging of helium/oxygen, argon/oxygen atmospheric pressure plasma microjet (2010).
- Joe Jordan, high school students, Saint Peter's Preparatory High School Project: Optical Emission Spectroscopy of an atmospheric pressure air and noble gas mixture plasma microject (2009-2010)
- Michael Rufolo, high school students, Saint Peter's Preparatory High School Project: Optical Emission Spectroscopy of an atmospheric pressure air plasma microjet (2009)
- Luan To, undergraduate student, Saint Peter's College Project: Study of the effect of different cathode material on the formation of self-organized patterns in a cathode boundary layer discharge (2009)
- Gagan Sapkota, undergraduate student, Saint Peter's College Project: Capillary dielectric boundary layer discharge: device assembly and imaging (2009)

- Justin Lo Re, undergraduate student, Saint Peter's College Project: Automation of gas feed and gas ratio control and optical emission spectroscopy of noble gas mixture plasma microjet (2010-2011)
- Ruixue Wang, graduate student, Poly Institute of NYU and Peking University, visiting scholar, Saint Peter's College Projects: Characterization of atmospheric pressure plasma microjet with various working gas, study of their interaction with liquid media and characterization of the plasma source as well as the liquid media before and after the interaction with plasma. Generation of new plasma sources (2010-2011)
- Dapeng Dong, graduate student, Stevens Institute of Technology; visiting scholar, Saint Peter's College Project: modeling of plasma sources with COMSOL (2011)

Student Achievements:

Kamal Shah won a gold medal in the 52nd Hudson County Science Fair for his research conducted in the CMST in 2009 (http://www.nj.com/news/jjournal/index.ssf?/base/news-4/126932552476100.xml&coll=3). He was also placed 2nd in Northern Jersey Junior Science and Humanities Symposium (certificate attached).

Kamal Shah also won a gold medal in the 53rd Hudson County Science Fair for further research conducted in the CMST in 2010 (http://www.nj.com/hudson/index.ssf/2011/03/two_winners_of_the_53rd_annual.html). He was recommended to compete in the Intel International Science and Engineering Fair in Los Angeles.

Kamal Shah was admitted to Rice University

Yacine Fares won a silver medal in the 53rd Hudson County Science Fair for his research conducted in the CMST in 2010

Yacine Fares was admitted to Princeton, Yale, Harvard and Columbia and chose to attend Harvard University.

High School Teachers:

A few local area high school teachers participated in research work in our labs funded through the PARSE Institute of Saint Peter's College.

Anthony DeCaro, Milton School
Project: Micro-Hollow Cathode Discharge Plasma Jet (2009)
Link to power point presentation:
(http://www.spc.edu/MSDocs/parse/microhollowcathodegaganjoseph.pps)

Robert J. Toegel, McNair Academic High School
Project: Cathode Characterization in Cathode Boundary Layer Discharge Microplasma (2009)
Link to power point presentation:
(http://www.spc.edu/MSDocs/parse/CCofMicroplasma.pps)

Frederic Williams, University Academy Charter High School
Project: Capillary Dielectric Barrier Discharge: Optical Emission and I-V characterization (2009)
Link to power point presentation:
(http://www.spc.edu/MSDocs/parse/capillarydbd3.pps)

VI. Interaction with Academia, Industry, and Federal Laboratories

There was direct collaborative research work done with the following national and international partners over the period of this research project. This is a list of the various established interactions:

Peking University, Beijing, China
Polytechnic Institute of New York University
Drexel University
UC Berkeley
University of Michigan, Ann Arbor
Old Dominion University
NYU Dental School
University of Medicine and Dentistry of New Jersey
Princeton Plasma Physics Laboratory
Case Western Reserve University
Texas A&M University
University of Notre Dame
University of Southern California
Stanford University

The United States Army Armament Research, Development and Engineering Center at Picatinny Arsenal
Algitron (joint STTR proposal)
Busek
The Linde Group